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Carbon Nanofiber Reinforced Polymers

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Introduction: Advanced defense platforms increasingly demand lighter-weight and higher-performing materials. The benefits of lightweight structural components are apparent in the form of increased fuel efficiency, improved mobility, and so on; however, savings in component weight must not come at the expense of functional performance. Whereas aluminum and titanium alloys can be used to reduce weight in many structural applications, even greater weight savings are possible through the use of high-strength polymer composites. The current thrust of our research is to determine the potential benefits of hierarchical structuring to achieve better functional performance. Hierarchical structuring is common in biological material (e.g., nacre, tendon, bone, and wood), yet the general principles and mechanisms by which hierarchical structuring influences functional performance is poorly understood. In this investigation, we examine the structural properties of a polymer nanocomposite whose matrix constituent exhibits an intrinsic hierarchical structure at length scales from 10^{-9} to 10^{-6} m.

Another strategy to achieve weight savings involves the consolidation of multiple functionalities into a single material system resulting in more efficient use of material and reduction of parasitic structural mass. Our group at NRL is actively pursuing the development of materials that simultaneously perform multiple roles, such as structure plus thermal or electrical conduction. The driving force behind the interest in structure/conduction multifunctionality is partly due to the widespread incorporation of densely packed electronic components in shipboard systems. These components produce large amounts of heat that, if not adequately managed, can magnify thermal signature and reduce the life or impair the efficiency of the components themselves. Multifunctional structure-conduction polymer composites might be a lightweight alternative to the thermal management approaches in use today (e.g., aluminum heat sinks).

Technical Approach: We propose the use of mass-produced and inexpensive, *discontinuous* carbon nanofibers to create a percolated fiber network within a polymeric matrix that will result in a nanocomposite material with enhanced mechanical, thermal, and electrical properties.

For the matrix material, we have selected a thermotropic liquid crystalline polymer (LCP) known commercially as Vectra A950. Liquid crystalline polymers exhibit liquid crystalline phases in regions of high shear of the polymer melt (thermotropic LCP) or at sufficiently high concentration in solution (i.e., lyotropic LCPs, a well-known example of which is the aramid Kevlar). This thermotropic LCP was selected owing in part to its processibility using standard thermoplastic processing equipment. More importantly, Vectra A950 is a main-chain LCP that produces a nematic liquid crystalline phase under shear deformation. An interesting result of the molecular alignment is the parallel formation of hierarchically ordered fibrillar structures with diameters ranging from 10^{-9} to 10^{-6} m. Because molecular alignment is induced by the deformation field, this material allows us to explore the influence of hierarchy on functional performance through control of deformation conditions during processing.

We initially selected vapor-grown carbon nanofibers (VGCF) as the reinforcing and conductive second phase because they are inexpensive (25¢/g) yet possess high mechanical and conduction properties akin to their much more expensive cousins, single-wall carbon nanotubes (SWNT - $500/g). This has enabled us economically to develop and refine our processing, testing, and characterization techniques.

A Brabender twin-screw extruder was used to fabricate LCP-VGCF filaments (up to 1.6-mm diameter at 0, 1, 2, 5, and 10 wt% VGCF). The filament diameter was controlled by varying the uptake speed of the semi-molten extrudate. Filaments were tested in quasi-static tension at room temperature. The tensile modulus of elasticity was calculated from the initial slope of the stress-strain curve, and the strength was calculated at the fracture load. Fracture surfaces of the tested samples were observed at high magnification using scanning electron microscopy (SEM).

Results/Summary: From the stress-strain histogram in Fig. 4, we can see that the addition of 1-2 wt% VGCF increased the modulus and strength of our LCP-VGCF nanocomposite by 40% and 20%, respectively. This magnitude of increase in mechanical performance with the addition of such small amounts of VGCF suggests that good interfacial strength is developing between the VGCF and LCP. This is also evident in the SEM images of the fracture surfaces (Fig. 5).

In Fig. 6, we see that the tensile modulus increases as the extruded diameter decreases. The largest diameter effects also occur at the 1-2 wt% VGCF levels. This dependence on filament diameter is interesting and likely due to a combination of VGCF and LCP molecular alignment. Stretching the LCP into thinner filaments forces a greater proportion of its molecules to align along the stretch direction, resulting in higher strength and stiffness. We also believe that the LCP molecular alignment process influences the alignment of VGCF
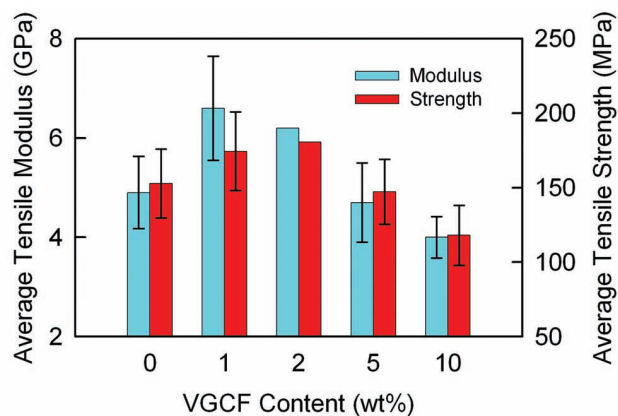
FIGURE 4
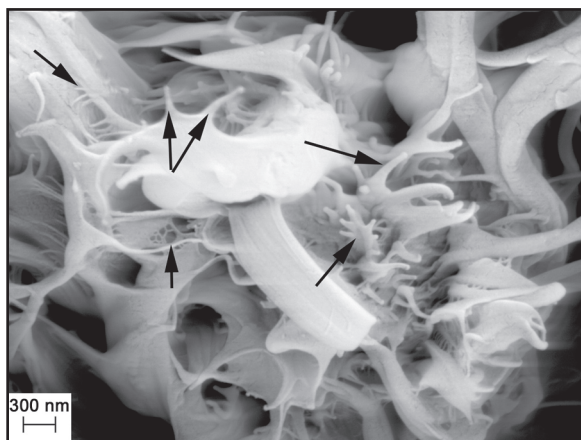Average modulus and strength as functions of VGCF concentration.

FIGURE 5
SEM image of the fracture surface of an extruded LCP-VGCF filament. The hierarchical nature of the LCP is demonstrated by the presence of numerous smaller-scale fibrils (indicated by arrows) formed by the splitting of larger-scale fibrils.
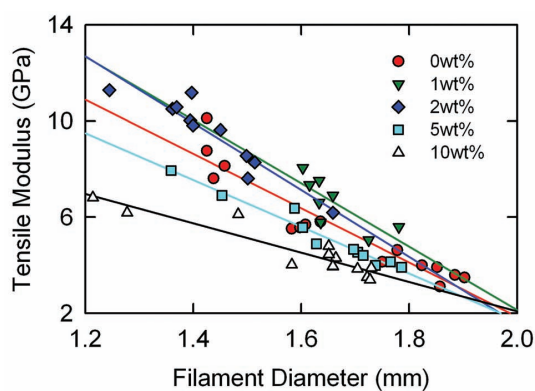

FIGURE 6
Tensile modulus as a function of extruded filament diameter.

resulting in improvement of its stiffening and strengthening effectiveness in the extrusion direction. Transmission electron microscopy, X-ray diffraction, and nanoindentation measurements are being made to assess quantitatively the connection between processing and LCP and VGCF alignment. Thermal and electrical conductivity measurements are also being made to assess the multifunctional potential of these hierarchically structured polymer nanocomposite materials.

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